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Shunt Capacitor Bank Switching Transients: A Tutorial and Case Study

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NSP

Capacitor Bank Switching

- Overview of recent installations at NSP
- Observations and trends
- Study work that must be done
- Tutorial on capacitor bank switching
- Brief overview of 115-kV case study
- Comments

MMTU Phase I

(Increased Power Transmission)

Station	Voltage	MVAR	Configuration
Red Rock	115 kV	240	3 x 80
Kohlman Lake	115 kV	240	3 x 80

MMTU Phase II

(Increased Power Transmission)

Station	Voltage	MVAR	Configuration
Forbes	500 kV	600	2 x 300

400 MVAR Thyristor Switched

MMTU Phase III

(Increased Power Transmission)

Station	Voltage	MVAR	Configuration
Prairie	115 kV	480	12 x 40 MVAR
Little Fork	230 kV	240	6 x 40 MVAR
Sheyenne	115 kV	200	5 x 40 MVAR
Roseau	230 kV	80	2 x 40 MVAR

Others
(Voltage/VAR Support)

Station	Voltage	MVAR	Configuration
Eau Claire	161 kV	320	4 x 80 MVAR
Parkers Lake	115 kV	240	3 x 80 MVAR
Aldrich	115 kV	240	2 x 120 MVAR
Elm Creek	115 kV	120	1 x 120 MVAR
Elliot Park	115 kV	80	1 x 80 MVAR
Rogers Lake	115 kV	240	3 x 80 MVAR

Others, Cont'd
(Voltage/VAR Support)

Station	Voltage	MVAR	Configuration
Koch Refinery	161 kV	80	1 x 80 MVAR
Split Rock	115 kV	160	2 x 80 MVAR
Cherry Creek	115 kV	40	1 x 40 MVAR
Lk Yankton	115 kV	40	1 x 40 MVAR
Buffalo Ridge	34.5 kV	80	Total Dist.
Traverse	69 kV	14	1 x 14 MVAR

Trends

- At least 4 GVAR installed in NSP system in recent years.
- Most installed at 115-kV and above
- LOTS of stored energy in cap banks
- Higher X/R ratio means less damping than is observed at lower voltage levels.
- More concern about switching transients

Types of Studies Needed

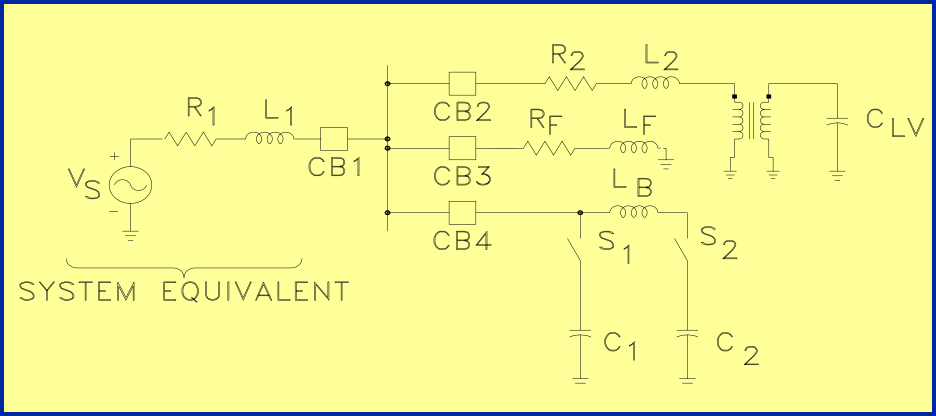
- Inrush/Outrush Current
- Transient Overvoltage (TRV)
- Voltage Magnification (Interaction with capacitors on nearby distribution system)
- Existing Equipment Ratings
  - Breakers
  - Surge Arresters
- New Equipment Ratings
  - Breakers
  - Surge Arresters
  - Inrush/Outrush Current-Limiting Reactors
- Current Transformer High Secondary Voltage

Getting Started -

Useful Reference Information

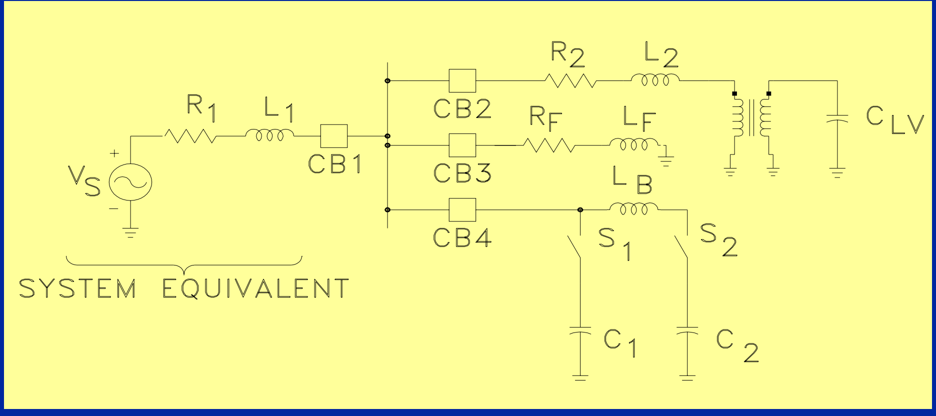
- A. Greenwood, Electrical Transients in Power Systems
- IEEE Std. C37.012-1979
- IEEE Standards Collection on Power Capacitors
- IEEE Tutorial - Application of Power Circuit Breakers
- IEEE Special Publication - Modeling and Analysis of System Transients using Digital Programs
- Other misc. papers

Learning the Basic Concepts of Capacitor Bank Switching



34.5-kV Per-Phase System

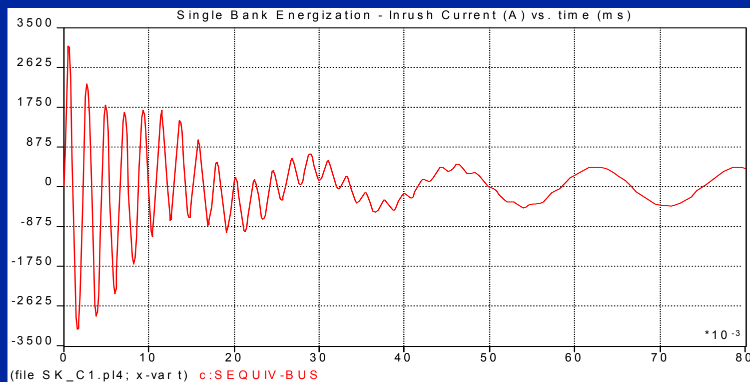
1 - Energization Inrush



CB1 and CB4 Closed, Close Switch S1.

Energization Inrush - First Bank C_1

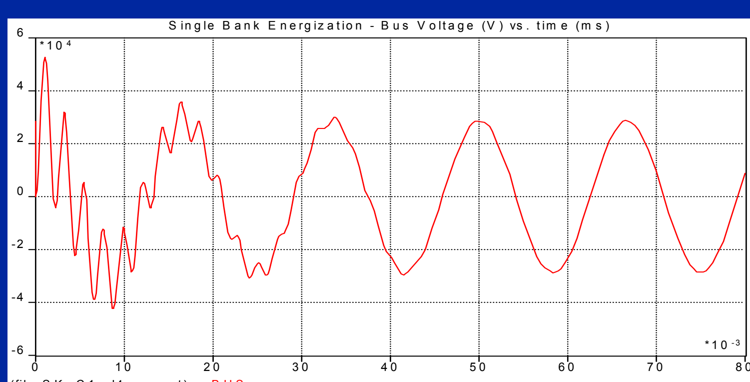
$$i(t) = \frac{V(0)}{Z_0}\sin\omega_0 t \qquad Z_0 = \sqrt{\frac{L}{C_1}} \qquad \omega_0 = \frac{1}{\sqrt{LC_1}}$$



Peak Current = 3041 Amps, Natural Frequency = 500 Hz

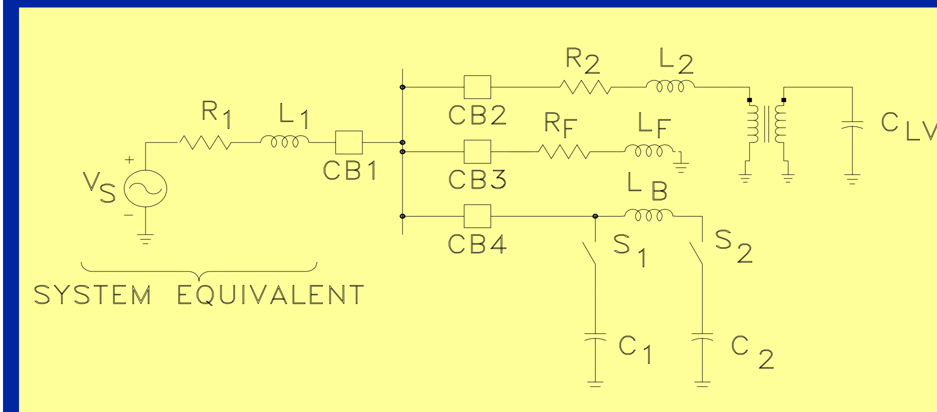
Energization Inrush - First Bank C_1

$$i(t) = \frac{V(0)}{Z_0}\sin\omega_0 t \qquad Z_0 = \sqrt{\frac{L}{C_1}} \qquad \omega_0 = \frac{1}{\sqrt{LC_1}}$$



Bus Voltage: Peak Voltage = 1.87 per unit

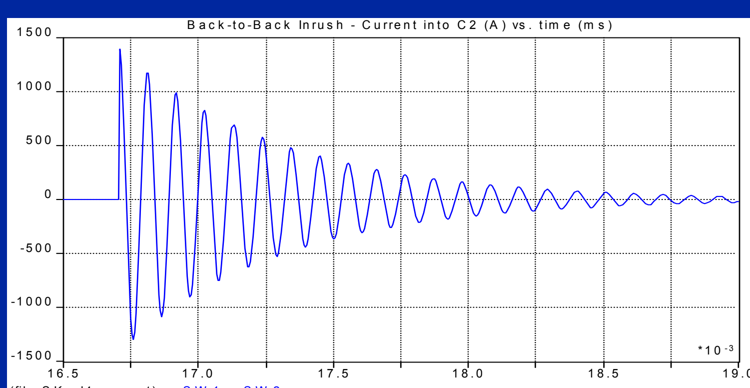
2 - Back-to-Back Energization



CB1, CB4, S1 Closed. Close Switch S2.

Back-to-Back Energization

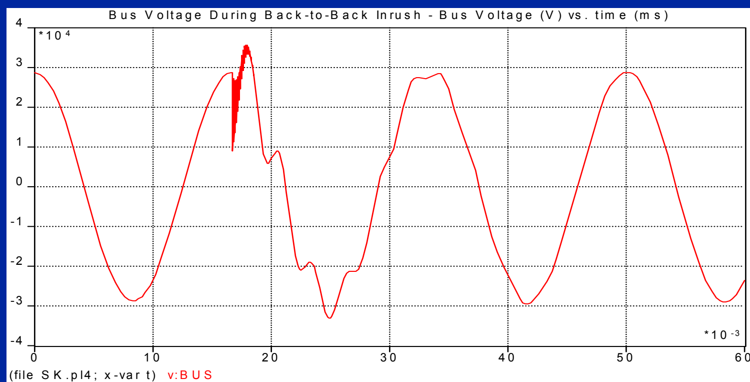
$$i(t) = \frac{V(0)}{Z_{01}} \sin \omega_{01} t \qquad Z_{01} = \sqrt{\frac{L_B}{C_{EQ}}} \qquad \omega_{01} = \frac{1}{\sqrt{L_B C_{EQ}}} \qquad C_{EQ} = \frac{C_1 C_2}{C_1 + C_2}$$



Peak Current = 1400 Amps, Natural Frequency = 9.4 KHz

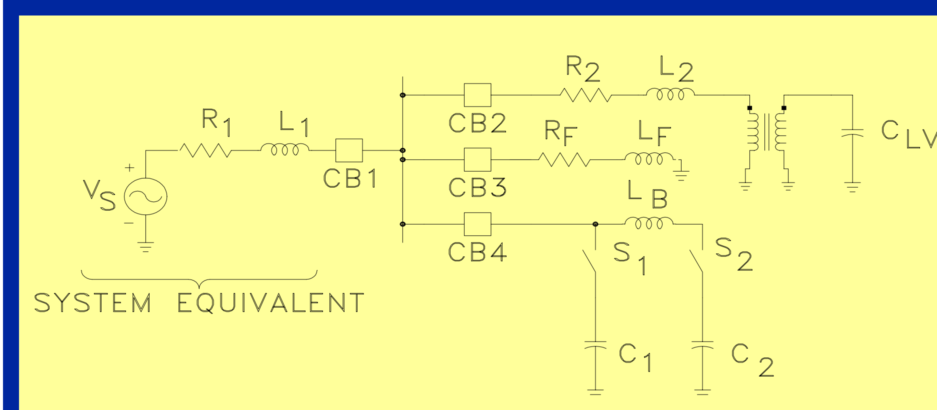
Back-to-Back Energization

$$i(t) = \frac{V(0)}{Z_{01}} \sin \omega_{01} t \qquad Z_{01} = \sqrt{\frac{L_B}{C_{EQ}}} \qquad \omega_{01} = \frac{1}{\sqrt{L_B C_{EQ}}} \qquad C_{EQ} = \frac{C_1 C_2}{C_1 + C_2}$$



Peak Bus Voltage = 1400 Amps

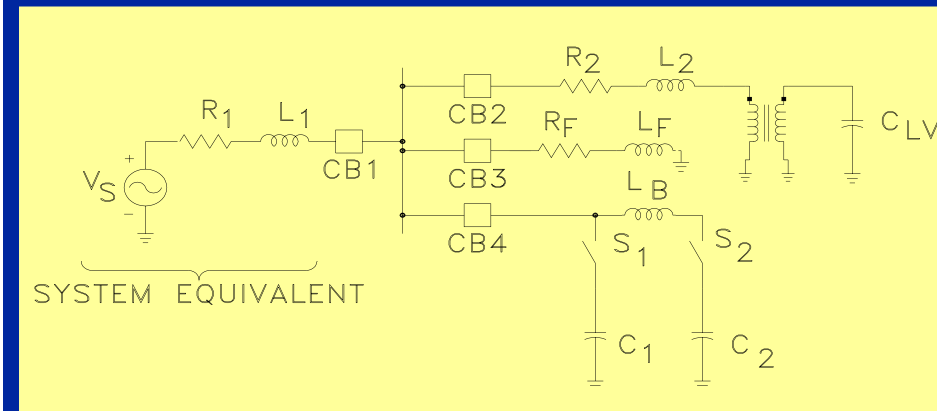
3 - Outrush Transient



$$i(t) = \frac{V(0)}{Z_{02}} \sin \omega_{02} t \qquad Z_{02} = \sqrt{\frac{L_F}{C_1}} \qquad \omega_{02} = \frac{1}{\sqrt{L_F C_1}}$$

CB1, CB3, CB4, S1 Closed. Fault on Feeder or Bus.

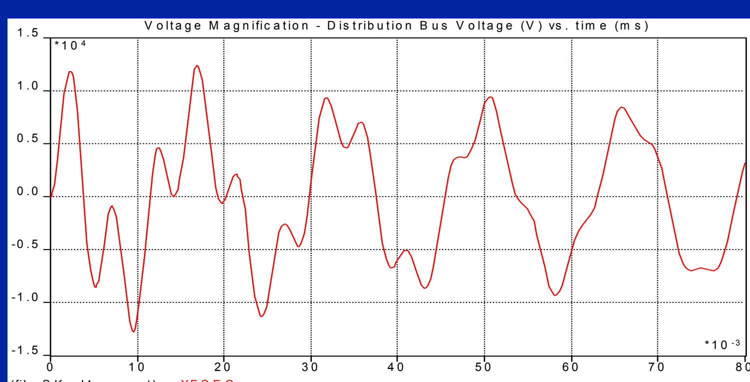
4 - Voltage Magnification



CB1, CB2, CB4 Closed. Close Switch S1 or S2.

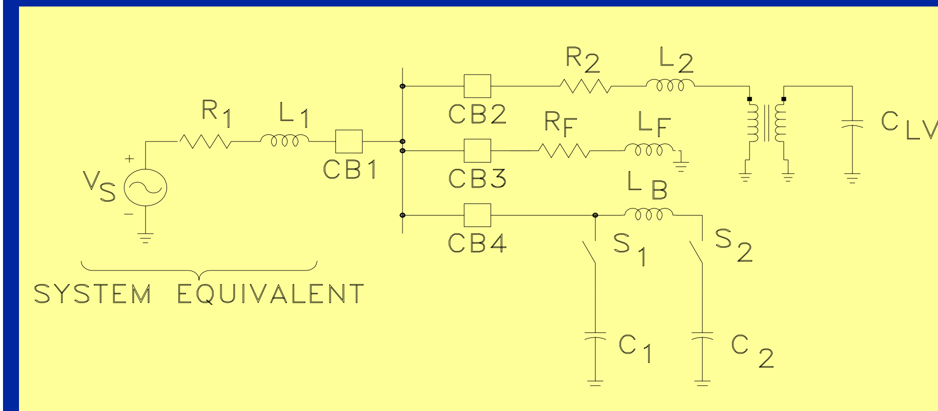
Voltage Magnification

$$\omega_0 = \frac{1}{\sqrt{L_2 C_{LV}}} = \frac{1}{\sqrt{L_1 C_1}}$$



Peak Distribution Bus Voltage = 1.76 per unit.

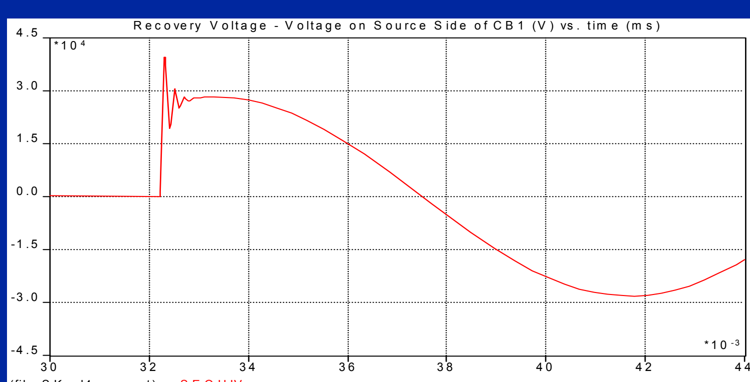
5 - Transient Recovery Voltage



CB1 Closed, Fault on Bus. Open CB1 to Clear Fault.

Transient Recovery Voltage

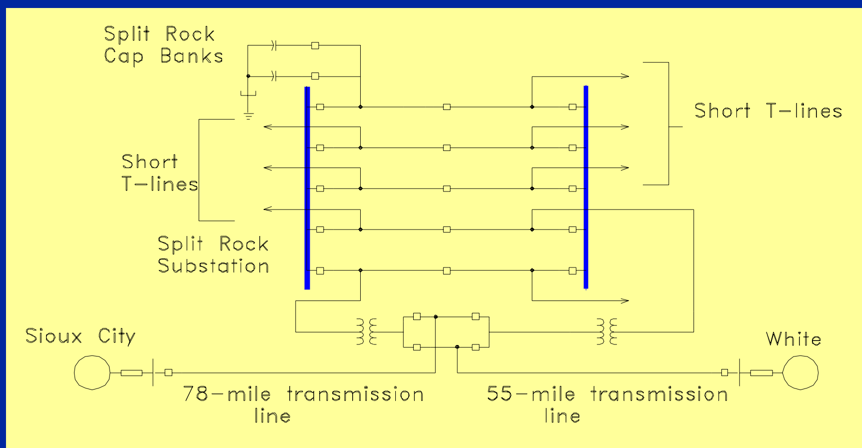
Oscillation between Circuit Breaker Bushing Capacitance and Source Inductance.



Peak Bus Voltage = 1.4 per unit, Frequency = 5 KHz.

Split Rock - A Case Study

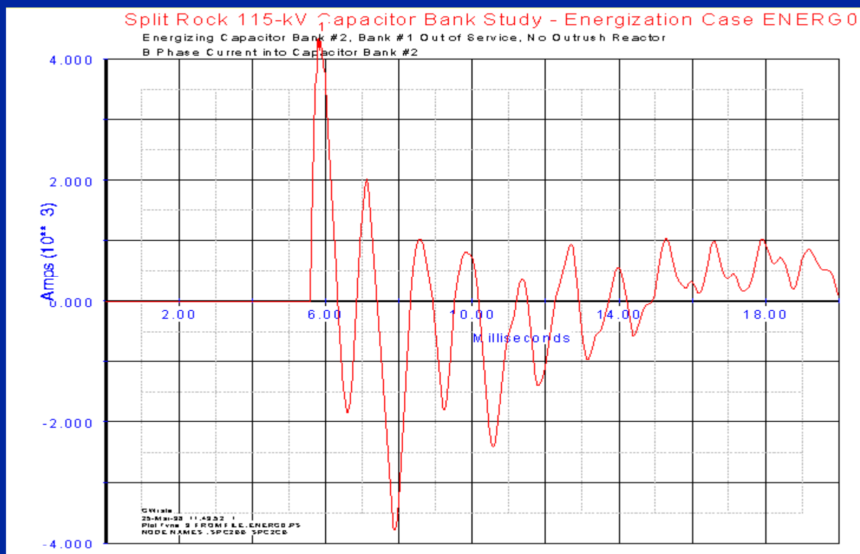
2 - 80 MVAR 115-kV Banks



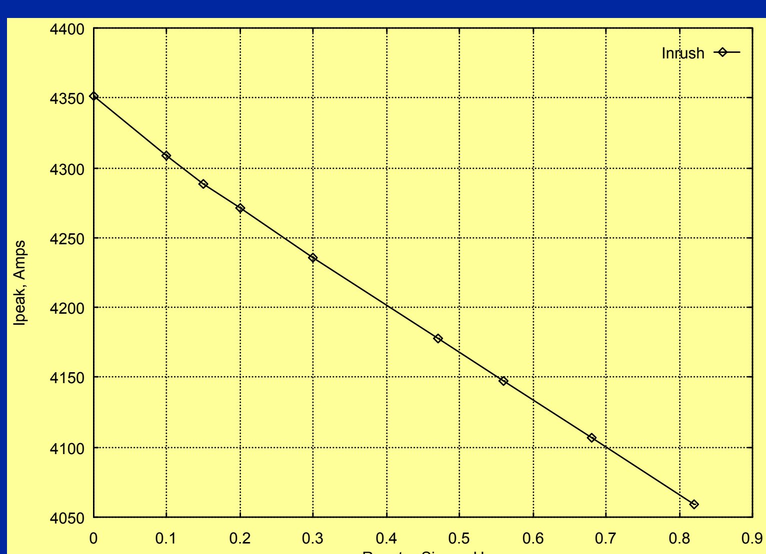
The Study Zone

- Multi-Port 60-Hz Thevenin Equivalent to model surrounding system
- Transformers - coupled R-L with core saturation and bushing capacitances
- Transmission Lines: distributed parameter for long lines. Coupled-Pi for very short sections
- Capacitors with parallel dissipation resistors
- RLC Coupled-Pi for Buswork

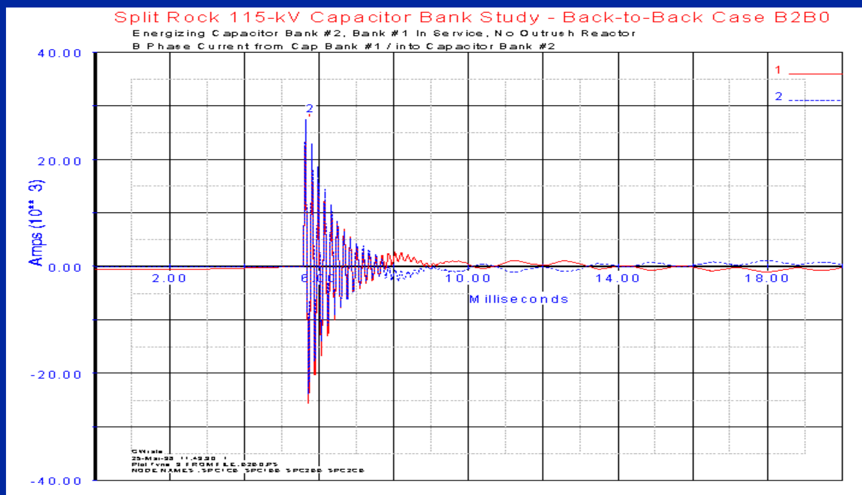
Single Bank Energization



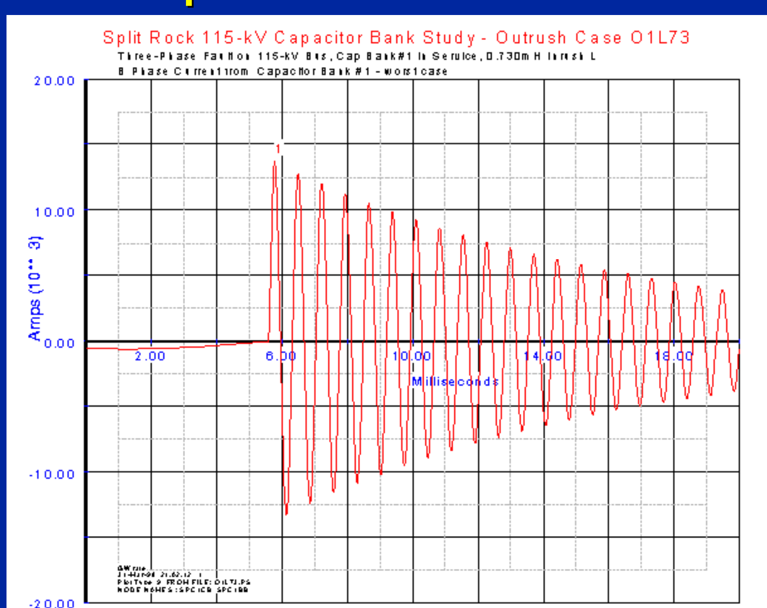
Inrush Reactor Sizing



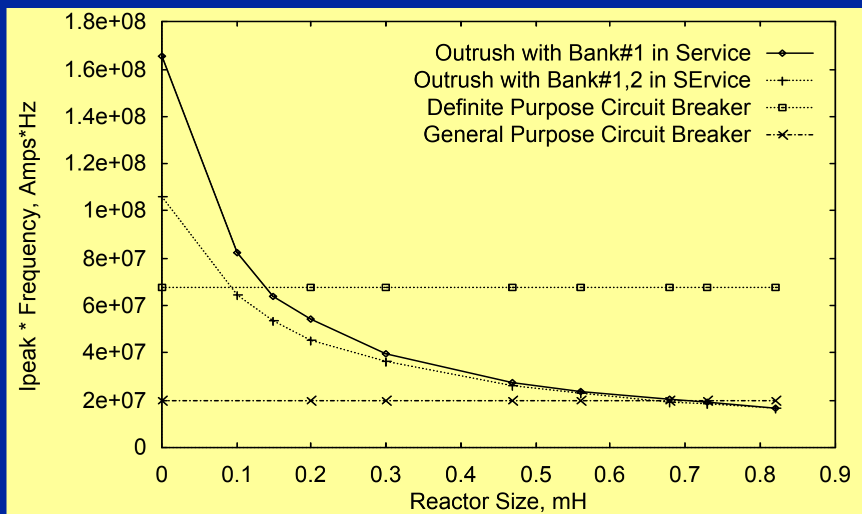
Back-to-Back Energization



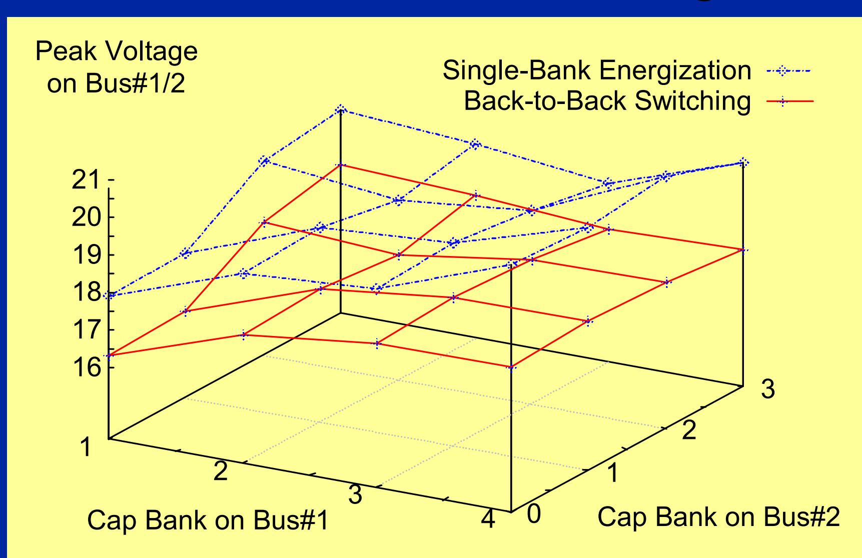
Capacitor Outrush Current



Outrush Reactor Sizing



Voltage Magnification Summary: Peak Distribution Bus Voltages



Other Concerns

- Statistical studies of peak currents and voltages in synchronous closing schemes
- Failure of synchronous closing scheme
- Time delay required to discharge banks in cases where reclosing is applied. Nonlinear voltage ringdown in cases when discharged through voltage transformers.
- Unintentional re-energization of bank before it has discharged. Worst case: energize when source voltage is opposite the polarity of the trapped charge.
- Changes in frequency response of system due to addition of capacitor banks.

CLOSING COMMENTS

- Studies performed over last 10 years and equipment specified seem to be correct.
- Ferroresonance involving the banks and regulator transformers has been observed for short periods of time. Nonlinearity of transformer makes it hard to predict. Some work in this area may be in order.
- Simulation results are only as good as the model. Transmission line and transformer models must be continually improved.
- Gathering equipment parameters can be most time-consuming part of simulation. Ask for complete equipment parameters when writing new equipment specifications.

COMMENTS?

QUESTIONS?